The Role of Robotic Outposts in Establishing a Permanent Presence in Space

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It's an honor to deliver the Third Annual Carl Sagan Memorial Lecture. Carl was involved with the exploration program from the very beginning with the Mariner 2 Flyby of Venus in 1962. He combined a deep scientific interest with a much broader view of exploration. Indeed, in his 1968 Condon Lectures, Carl emphasized that perspective was the fundamental return of exploration. Although we have just begun the third era of exploration, we need an ever enlarging view of the future so that we can shape that future, a future in which there is a permanent presence elsewhere in the Solar System.

I will look forward to an era in which robotic outposts establish a permanent presence in space. The ideas and illustrations are meant to be notional rather than specific roadmaps, with some thoughts about key technologies and public engagement. The ideas came from across the Agency, from industry, and from universities, and I'd like to acknowledge the many contributions.

The Eras of Space Exploration

The first era emphasized "getting there"; the engineering and science challenges were focused on getting to another place in the Solar System. The first planetary mission was the Mariner 2 flyby of Venus in 1962. In 1965, Mariner 4 (Figure 1) flew by Mars and returned the first digital images of another world -- at 8-1/3 bits per second. Although these missions yielded important information about the planets, the scientific return was dominated by the engineering challenges of deep space.

**** Figure 1: The First Era****

The first era continued through the 1960s, setting the stage for the second era, where the challenge shifted to "finding out what's there." Since so little was known about other bodies in the Solar System, large, comprehensive observatories included many scientific instruments and wide bandwidth communication to send the wealth of data back to Earth. These missions provided a global perspective of the many worlds that share the Solar System with Earth; several of these missions are shown in Figure 2. Viking conducted the first in situ analysis of the Martian surface, and Magellan mapped 95% of the surface of Venus. Voyager opened up the outer Solar System, revealing dozens of diverse worlds. Galileo is now in orbit around Jupiter, examining in detail the distinctive Jovian satellites, and beginning in 2004 Cassini will explore Saturn and its moon, Titan.

**** Figure 2: The Second Era****

The second era, with its large, comprehensive missions undertaken about once a decade, provided a global perspective that has revolutionized our understanding of the Solar System and set the stage for the third era. In the third era, the challenge is one of "going often, landing, and bringing samples back." Figure 3 shows some of the missions planned for this era; spacecraft will land on Mars and eventually other bodies, and bring back samples from comets, asteroids, and the Sun. The third era brings us a local perspective of other worlds and requires going often so as to visit many distinctive places. The challenge is to devise the technology and innovations that will reduce mission cost so we can afford to go more often.

**** Figure 3: The Third Era****

While the first and second eras were closely related, there are significant differences between the second and third eras (Table 1). In the second era, missions were individual, major projects. The mission would take about a decade to accomplish and typically cost about $1–$2 billion. In the third era, programs are sets of smaller, linked projects that together accomplish the overall program goals. The second era was also characterized by global views and remote sensing, while the third era presence on another planet reveals the planet on a human scale rather than a global scale, providing much broader public engagement. But the challenge of going much more often is building systems for one-tenth or one-twentieth of the cost of second era missions.

**** Table 1: Second and Third Era Characteristics****

Although the third era is just beginning, it will set the stage for a fourth era, one of "going and staying" – an era in which robotic outposts establish a permanent presence elsewhere in the Solar System. This next step will depend on developing the technologies to systematically put in place systems that can effectively bring out there back here through the power of communication. Although Mars is a focus of many near term missions, this capability could be established any place in the Solar System.

Table 2 contrasts the challenges of the present era with those of the fourth era. Surface missions of the current era are episodic, with occasional surface activities lasting 60–90 days; fourth era missions will emphasize continuous, cooperative operation on the surface of another body. Localized mobility near the landing site will be transformed into long-range mobility; and limited power and limited duration missions will be replaced by sustained, substantial power. The limited communications of the third era will be expanded to wide bandwidth, continuous communication. Finally, the current era of bringing all the resources from Earth will merge into an era in which we begin using what is out there.

**** Table 2: Third and Fourth Era Characteristics****

The Role of Robotic Outposts

There are two broad areas in which robotic outposts will contribute: advanced scientific studies and preparation for human exploration. Continuous presence will enable scientific activities that cannot be accomplished by missions limited to brief surface studies or to bringing back a limited number of samples. With the development of miniature surface laboratories, many more samples can be studied in place than can be returned to Earth. *In situ* analysis will allow a much more comprehensive search for present or past life on other bodies (on Mars in particular) and a more detailed study of their geological, atmospheric, and climatological history and evolution. Robotic outposts can also prepare the way for sustained human exploration through an increased understanding of the environment and its resources and by establishing some of the infrastructure and technology needed for eventual human presence in deep space. Finally, robotic outposts will have the added benefit of fostering greater public engagement, as places out there are experienced back here, not just by scientists, but by the public at large.

Advanced Scientific Studies

One of the key characteristics of life is that it creates chemical disequilibrium, producing changes in the abundances of several elements relative to their abundances in the Solar System as a whole. For some elements (such as phosphorus) there is no change from Solar System abundances; for others, such as hydrogen, carbon, nitrogen and oxygen, the differences are substantial. Life, if it exists or has existed on other worlds, should produce enhancements in certain elemental abundances that may be observable in the residues left behind as well as in any extant life forms.

One of the challenges is the systematic analysis of elemental abundances. One possibility would be to use a laser to drill into the surface of Mars. In the third era, mechanical drilling is limited to brief periods (e.g., 90 days) and limited depths (e.g., 10–100 meters). Future laser ablation techniques could not only drill a hole, but create a vapor of the material that can be analyzed spectroscopically. With robotic outposts that have greater power reserves than current missions, drilling and analysis could be undertaken for long periods (years rather than days) and greater depths (kilometers rather than meters). This may permit drilling to the depths where there was, or is, liquid water.

Another example of an analysis system is ultraviolet Raman spectroscopy. The ultraviolet portion of the wavelength spectrum is sensitive to RNA and DNA molecules. Raman spectroscopy, in which the wavelength shift depends on the nature of the molecules scattering the light, could be a remarkably sensitive technique for detecting organic material within cracks and crevices in rocky material. Such a laboratory in a robotic outpost might provide evidence as to whether there ever was life on Mars or whether there is life anywhere there today.

There are other ways in which robotic outposts could support space science. The Martian polar terrain is layered; the depositional build-up preserves a record of past climate. Evaluating the water, carbon dioxide, and isotopic composition of the carbon and oxygen content layer by layer (and therefore epoch by epoch) will provide a history of the climate on this neighboring planet and may yield important clues to the circumstances critical to the origin and evolution of life.

Preparing the Way for Human Exploration

There will be an increasing linkage between human and robotic exploration as the program evolves, beginning with the current robotic phase of sending landers and rovers to Mars to conduct initial *in situ* studies. By the end of the coming decade, we may begin returning samples to Earth while preparing for robotic outposts, including the advanced *in situ* science capabilities mentioned above. The evolution in robotic technology would be accompanied by advances in the communications nodes in orbit around Mars.

The current Mars program includes the development of several instruments designed to increase our understanding of the radiation and chemical environment of Mars. The Mars Environmental Compatibility Assessment (MECA) experiment includes an atomic force microscope for analyzing in detail the material properties of the surface; electrostatic characteristics will be measured and chemical properties will be assessed for any hazards they might pose to human presence on Mars. A Mars *In Situ* Propellant-Production Precursor (MIP) experiment, under development by the Johnson Space Center, uses zirconia to convert CO_2 into drops of oxygen – an exploratory step towards i*n situ* resource utilization. A third instrument is designed to measure the Martian radiation environment both on the surface and in orbit. The opportunities for deploying these and related instruments will be developed as part of the revised Mars mission architecture.

Public Engagement

The exploration of Mars on a human scale is broadly engaging. In May of 1999, high school students were operating the Rocky-7 rover in the Mojave Desert via the World Wide Web. Six high schools -- five in the U.S. and one in Finland -- were part of this demonstration.

An outpost with a wide bandwidth link to Earth in conjunction with advanced desktop software will make possible individual participation in the surface exploration of other worlds. Making other places in the Solar System accessible on a human scale will greatly increase opportunities for public engagement, especially students.

<u>Establishing and Evolving a Permanent Presence</u>

As technologies mature and scientific understanding increases, one or two locations might be chosen for the incremental development of a robotic outpost. Although Mars might be chosen, the first such place may well be the Moon or an asteroid. A notional illustration of an intermediate stage of development is shown in Figure 4.

Initially, solar power would provide energy to process materials, generate fuel from *in situ* resources, and assemble a drilling system for boring into the surface. Such an outpost could evolve with additional sources of power and longer range rovers. This incremental approach would provide new capability sequentially as we learn by doing, with the goal of expanding the capability of an outpost to support exploration in an ever increasing radius around the basic power and resource node.

**** Figure 4: Intermediate Outpost (Rovers, Drill, *In Situ* Resource System) ****

Incrementally expanding communications nodes can also be visualized. Currently, a polar orbiting spacecraft flies over a lander only twice per day, relaying about 100 megabits/day to Earth. A continuous presence requires much wider bandwidth such as would be provided by a network of communication/navigation microsatellites and a larger areostationary relay satellite. A network of six microsatellites could be built up incrementally, providing telecommunications capability of 10 gigabits per day with contact every two hours. They could also carry a Global Positioning Satellite-like navigation system for accurately locating systems on the surface of Mars. The addition of an areostationary spacecraft hovering over the robotic outpost site would provide 100 gigabits of data per day. Real time video streaming would then be possible, creating the opportunity for a virtual presence on the surface of another world. Such a communication system might eventually become a node of an Interplanetary Internet.

Key Technologies

Deep space high bandwidth communication is just one of the technical challenges posed by outposts. Other challenges include precision landing, miniature biochemistry labs, mobility systems, *in situ* resource utilization, and power. Precision landing within 1 kilometer of a fixed target is essential to the incremental development of an outpost. Current landing precision is on the order of 100 kilometers, so significant improvement is needed, including advances in maneuverability during the terminal descent and landing.

For robotic outpost science, one might imagine microlaboratories for analyzing material collected by rovers or brought up from deep beneath the surface. Such a microlaboratory might use microfabrication technology to provide, for example, capillary electrophoresis as well as laser-induced fluorescence for sample analysis.

Mobility is also important to a permanent robotic presence. In 1997, the Sojourner rover on Mars Pathfinder had a range of about 100 meters and a lifetime of about 90 days. Sample acquisition rovers will need a longer operating range extending to hundreds of kilometers, lasting for years, and operating autonomously on the surface. Aerial mobility (balloons and airplanes) may provide greater range but shorter duration.

Subsurface sampling is also important, because liquid water may be present deep beneath the surface. Liquid water is not only the key to the search for life, but is also essential for developing fuels and sustaining human exploration. Current sampling capability is limited to the top few meters of soil.

In situ resource utilization is another technology development area. Although solar power will be adequate for a small scale demonstration, a full scale system will likely require higher power than can be provided by solar energy alone.

Paving the Way for Future Exploration

Beyond *in situ* exploration, robotic outposts can further expand our perspective of the Solar System and pave the way for future exploration. They could be established on various bodies in the Solar System: asteroids, comets, the moons of Jupiter and Saturn, as well as Mars. Outposts could support a new era of scientific exploration and make these other worlds a part of our own experience here on Earth, not only for engineers and scientists, but for the public as well. Ultimately, such outposts could pull humans deeper into space, expanding human as well as robotic presence outward into the Solar System.

Acknowledgement

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FIGURE CAPTIONS

Figure 1.

The first era emphasized the engineering and science challenges of reaching and operating at another place in the solar system. Mariner 4 flew by Mars in 1965, returning the first digital images of another planet, including this view of the Southern Highlands.

Figure 2.

The second era provided global exploration of the solar system. The Viking program sent two orbiters and two landers to Mars in 1976. Between 1979 and 1989, Voyager spacecraft visited Jupiter, Saturn, Uranus and Neptune, and in 1990 Magellan began mapping Venus. Galileo entered Jupiter orbit in 1995, dropping a probe into the giant planet's atmosphere. Cassini will orbit Saturn in 2004, dropping the ESA Huygens probe into the atmosphere of the moon Titan.

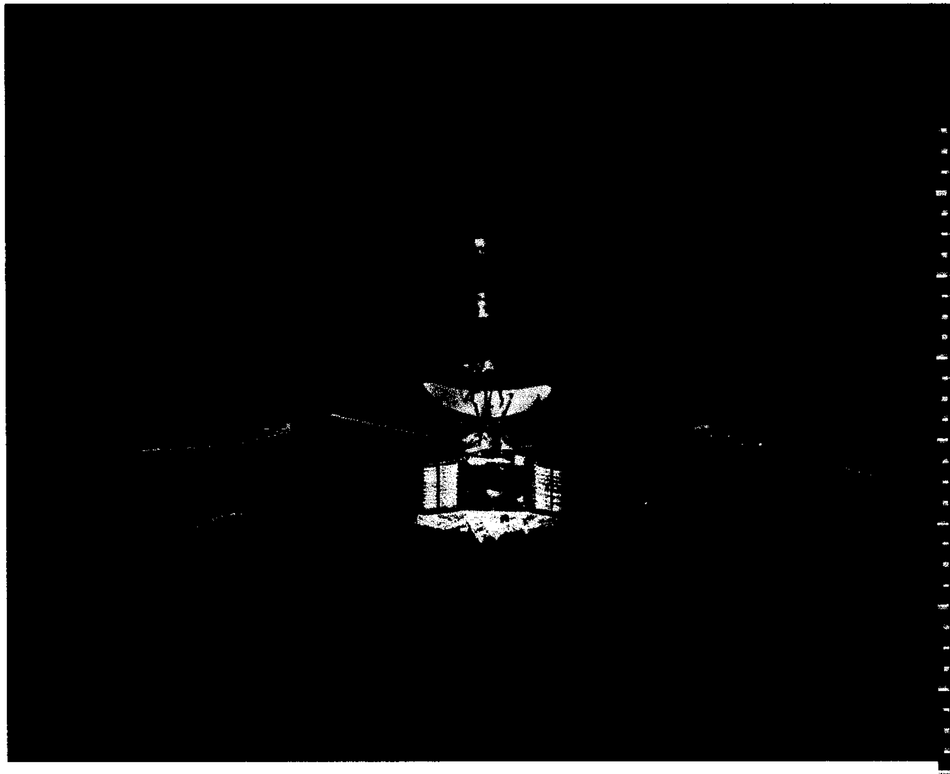
Figure 3.

The third era began with the landing of Mars Pathfinder in 1997, followed by Mars Global Surveyor (also in 1997), Deep Space 1 with its ion drive (1998) and the Stardust mission to obtain a sample of comet material (1999). Future missions include, for example, Genesis, which will return a sample of solar wind to Earth, Mars orbiters and landers, and a Europa orbiter.

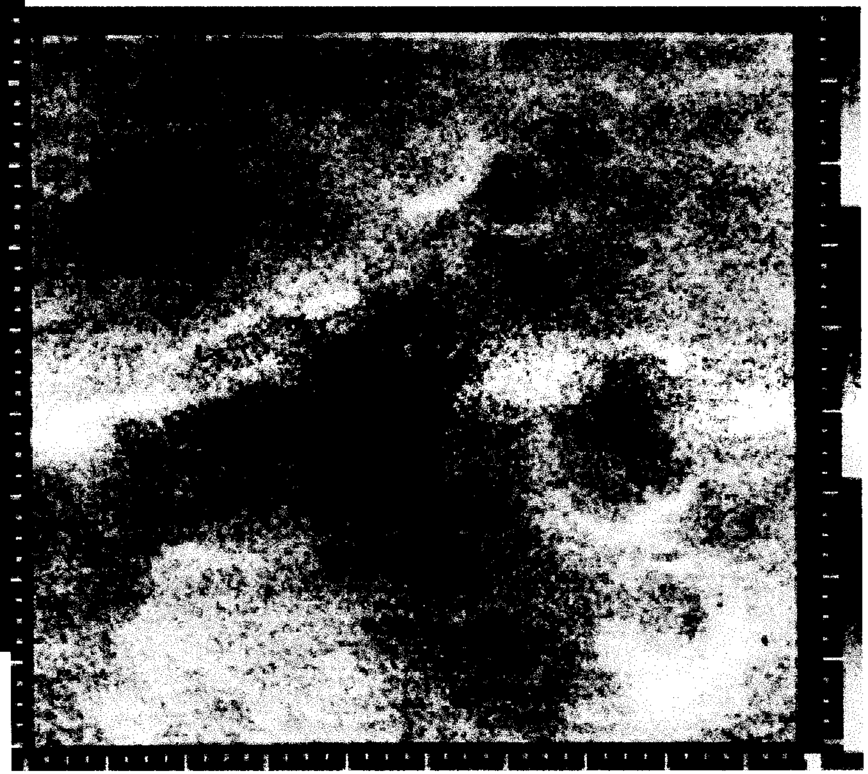
Figure 4.

The fourth era establishes a permanent presence elsewhere in the solar system. This is a notional illustration of an early robotic outpost. Solar arrays flank an *in situ* resource utilization system, while in the foreground two rovers are assembling a drill.

Figure 1. The First Era: Getting There



Mariner 4



Mariner 4 View of Crater Rims - Southern Highlands of Mars

Figure 2. The Second Era: Finding Out What's There

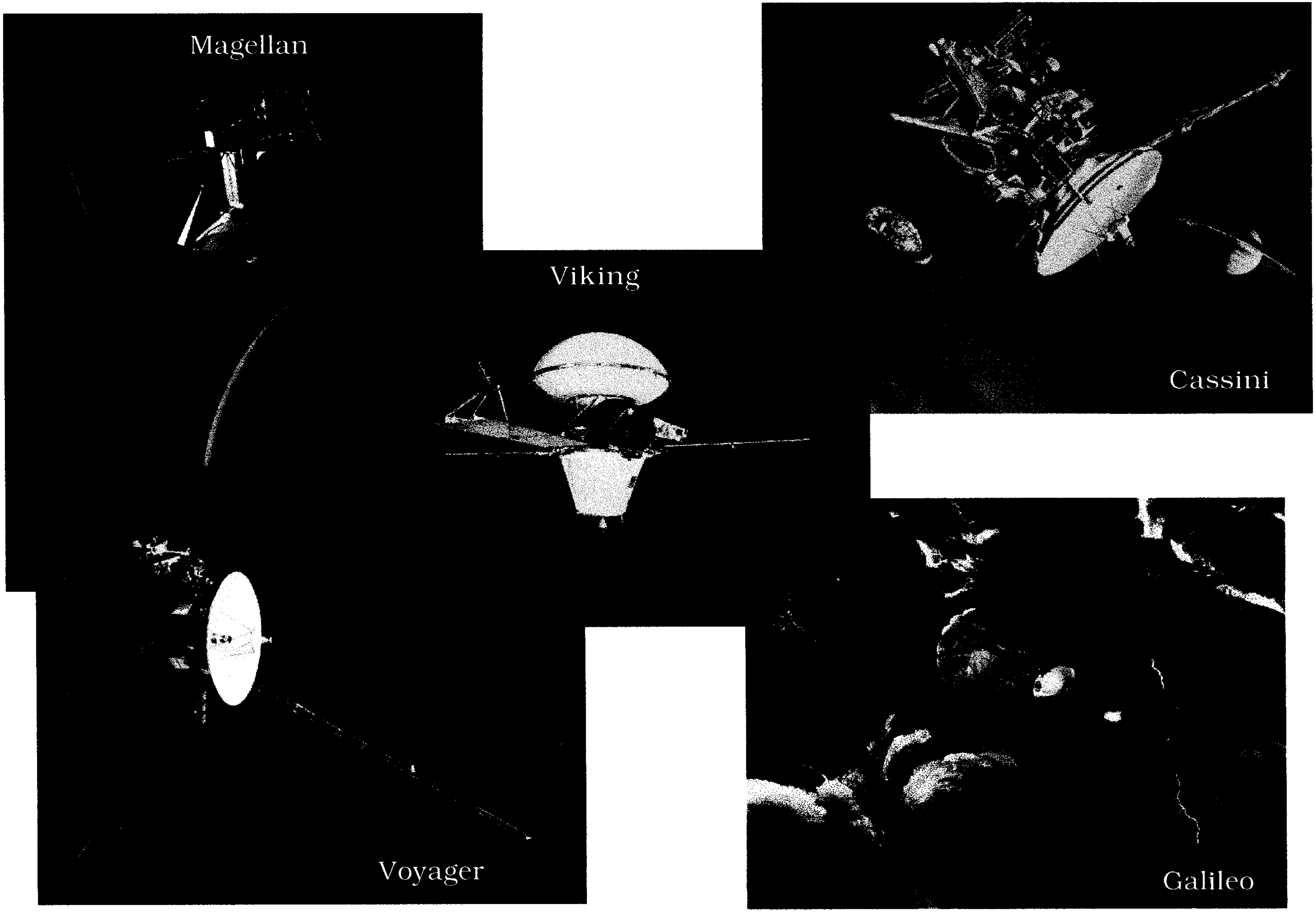


Figure 3. The Third Era: Going Often, Landing, and Bringing Samples Back

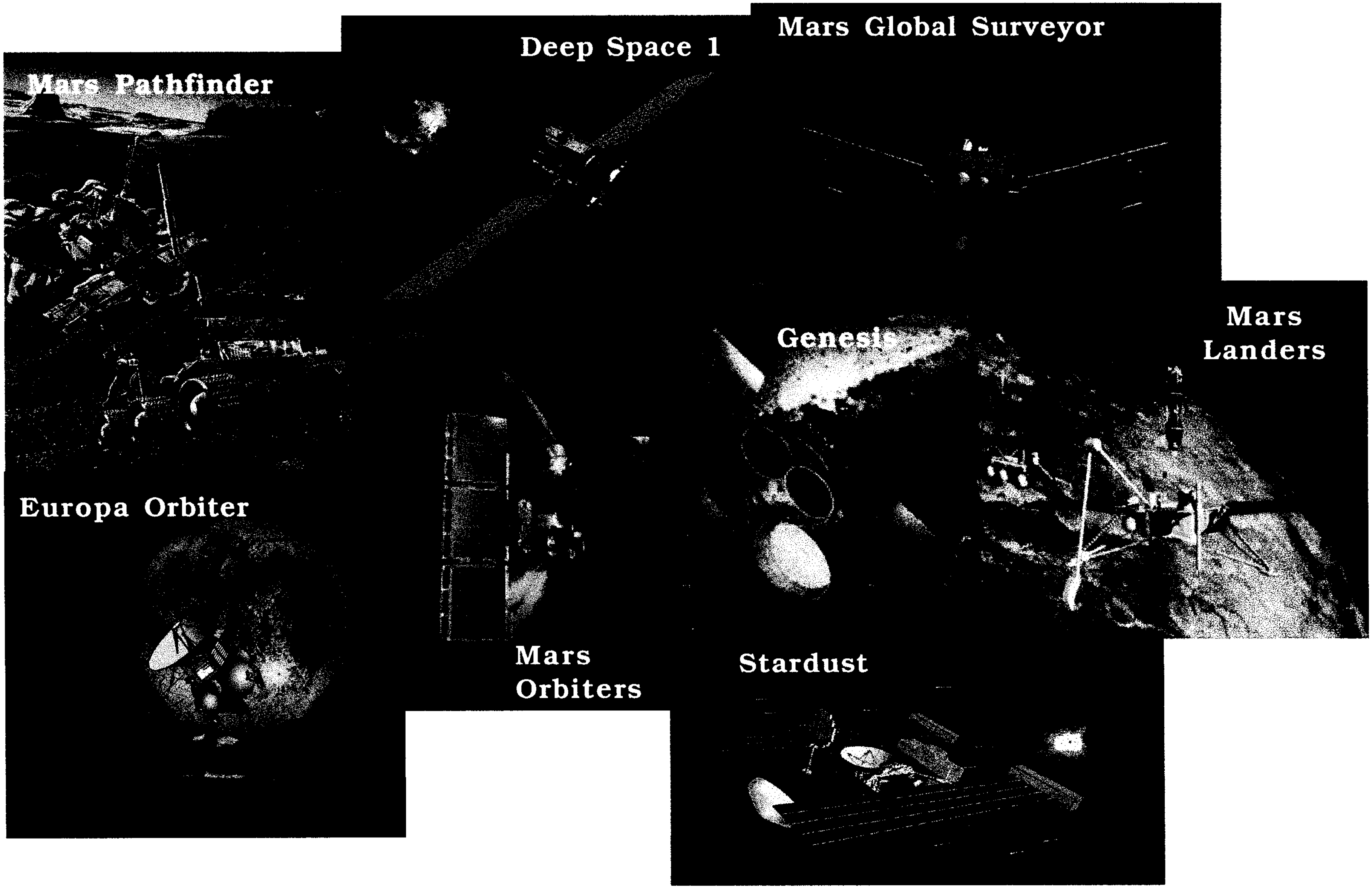


Table 1. Second and Third Era Characteristics

Second Era	Third Era
Individual Projects	Programs of Linked Projects
Large, Comprehensive Observatories	Small, Focused Systems
Global Scale Exploration	Local Scale Exploration
Remote Sensing	*In Situ* Sensing

Table 2. Third and Fourth Era Characteristics

Third Era	Fourth Era
Episodic Surface Activities	Continuous, Cooperative Operation
Localized Mobility	Long Range Mobility
Limited Power	Sustained, Substantial Power
Limited Communications	Continuous, High-bandwidth Network Communication
Bring Resources from Earth	Use *In Situ* Resources